Investigations on Textile Fibres.

By W. HARRISON, M.Sc.

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[PLATES 5 AND 6.]

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Although fibres form the most important raw material in the textile industries, few or no attempts have been made to investigate their fundamental properties. On this account most of the phenomena met with in the treatment of textiles have not been explained. The most important of these phenomena are those which occur during the application of stress, heat, and moisture.

An opinion commonly accepted by workers in the wool industries is that heat and moisture combined soften wool and render it plastic. This opinion appears to be right in principle, but is only qualitative, since wool exhibits plasticity under ordinary conditions. With regard to cotton, numerous investigations have been made on its chemical derivatives and their products of hydrolysis, but little attention has been paid to its physical properties.

It is known that the treatment of cotton, while under tension, with concentrated solutions of sodium hydrate, produces changes in its physical state resulting in an increase in lustre. This process is known as mercerisation. An explanation of the increased lustre was first put forward by Lange,* who stated that the surface of the fibres was rendered much smoother by the treatment. Hübner and Pope† were unable to confirm Lange's observations, and suggested that the increased lustre was due to reflection from spiral grooves on the surface of the fibre. The author‡ proved by means of photomicrographs that Lange's theory was substantially correct, but that the shape of the fibre in cross-section had an important bearing on its lustre. In the the same papers it was shown by photographs taken in the Cardioid ultramicroscope that a change in the state of aggregation of the cellulose in cotton fibres was produced by mercerisation. Further, by the use of polarised light, an explanation was obtained for the fact that cotton fibres shrink in length when treated with sodium hydrate solution while in a loose condition.

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* 'Farber-Zeitung,' p. 197 (1898).

† 'Journ. Soc. Chem. Ind.,' vol. 23, p. 410 (1904).

‡ 'Journ. Soc. Dyers and Colourists,' vol. 31, p. 1981 (1915); also 'Trans. Nat. Assoc. Cotton Manufacturers,' Boston, U.S.A., vol. 101, p. 201 (1916).

Polarised light has been used by several authors for the examination of nitrated cotton: Chardonnet* and Liebschutz†. Ambronn‡ stated that an idea of the percentage of combined nitrogen could be obtained in this way. De Mosenthal§ found that nitrated cotton of the same degree of nitration, prepared by different methods as to temperature, acid mixture, and time of immersion, showed different colours in polarised light, and that the appearance differed with the raw material used. No explanation of these results was offered.

The investigations described in the present paper were undertaken with a view to determining some of the fundamental properties of textile fibres which govern their behaviour in manufacturing processes, and thereby to establish a scientific basis for research into such processes.

Effect of Stress, Moisture, and Heat on Textile Fibres.

It is a well known fact, first established by Sir David Brewster in 1814, that substances of a colloidal nature such as glass, gelatine, and indiarubber, exhibit double refraction when subjected to stress, but lose this property when the stress is removed. Permanent double refraction can be produced in these substances in different ways: in the glass by heating it nearly to the melting point and cooling rapidly, in the gelatine by applying considerable pressure, and in unvulcanised indiarubber by subjecting it to distortion while warm and cooling it in position. The permanent double refraction produced in these different ways is due to internal stresses resulting from the permanent strains left in the materials. These stresses can be removed from the glass by annealing, from the gelatine by soaking in water, and from the indiarubber by heating or soaking in a solvent.

It is known that all textile fibres are doubly refracting, and it will be shown in the course of this paper that this property is due to the presence of internal stresses.

By the application of external stresses in certain directions the double refraction of all fibres is increased. The effect of pressure was investigated by compressing the fibres between a thick glass plate and a grooved celluloid film placed on a second glass plate, the whole being placed on the stage of a microscope and examined in polarised light between crossed nicols. By this method, the difference between the compressed and uncompressed portions could be clearly seen.

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* Compare Carl Suvern, 'Die Künstliche Seide,' p. 23 (Berlin, 1900).

† 'Moniteur Scientifique,' p. 119 (1891).

‡ 'Koll. Zeit.,' vol. 13, p. 200 (1913).

§ 'Journ. Soc. Chem. Ind.,' vol. 26, p. 444 (1907)

The effect of gradually increasing the pressure on a fibre of English wool, until compressed level with the top of the grooves in the celluloid film, is illustrated in Plate 5, fig. 1. Part of the illumination is due to the effect of the pressure on the celluloid, but this is relatively small and does not interfere with the results, which can also be obtained by compressing crossed fibres between parallel glass plates. The interference figures shown in fig. 1, B and C, indicate spreading of the fibre substance in all directions away from the centre of pressure, *i.e.*, the point of contact between the cylindrical fibre and the cylindrical surfaces of the grooved celluloid film. When the portions in the hollows of the groove became compressed, they spread towards the original centre of pressure and the interference figures disappeared, fig. 1, D. The maximum pressure applied was approximately 5 tons to the square inch of the surface of contact between fibre and celluloid, and in all cases the latter retained an impression of the fibre, showing that celluloid is not relatively very hard compared with wool and cotton.

No interference figures were observed during the gradual application of pressure on cotton fibres, fig. 2. Spreading of the fibre substance only occurred where directly under pressure even when compressed level with the top of the grooves in the celluloid.

The cotton fibre thus offers greater resistance to deformation than the wool fibre.

With both wool and cotton, after removal of the pressure, the fibres did not return to their original shape and the increased double refraction in the compressed portions remained permanent. This is illustrated with wool in fig. 3 and with cotton in fig. 4. The bright portions in fig. 3, C, and fig. 4, C, are evidence of internal stresses resulting from the permanent strains left in the fibres after compression. The tendency to return to its original shape is small in the case of wool even when only slight pressure has been used, but is somewhat greater with cotton. For the photomicrographs a cotton fibre mercerised under tension was chosen on account of its greater regularity in structure; ordinary cotton behaves in exactly the same way.

Similar experiments were made with dry fibres of silk, linen and ramie, and these also were permanently deformed by pressure and retained internal stresses, but the effect was not so pronounced as with wool.

Fibres deformed in the manner described above were found to return to their original shape when placed in cold water. This is shown with wool in fig. 3, E, and with cotton in fig. 4, E. This return took place almost immediately with wool, but more slowly with cotton, particularly when high pressure had been applied. The length of time under compression appeared to have an influence on the result obtained.

Similar results were given by fibres which had been bent or twisted; when placed in cold water they gradually returned to their original shape. Fibres doubled and twisted as in figs. 6 and 7, placed loosely in cold water, gradually untwisted and straightened themselves out. This occurred quite rapidly when the fibres were doubled and the free ends held tightly while twisting. On the other hand, when the fibres were first twisted on their axes and then doubled, untwisting took place very slowly and only from the free ends onwards. This retardation is due to the fact that when twisted in this latter manner, the torsional stresses in the one portion of the doubled fibre tend to balance those in the other, and it is only by the untwisting of the free ends of the fibre that these torsional stresses are released.

Fibres subjected to a limited amount of extension when dry do not return to their original length when kept loosely in a dry atmosphere, but do so rapidly when placed in water.

The effect of a humid atmosphere is similar to that of cold water, but the release of internal stresses produced by deformation takes place much more slowly with the former.

The results obtained by compressing wet fibres at the ordinary temperature agreed with what was expected from the above, the fibres behaved like other elastic bodies. The wool fibre appeared to be more elastic than any other.

Experiments were made at higher temperatures by the use of a grooved aluminium sheet in place of the celluloid, the fibres being compressed between this grooved plate and a plain one, and in all cases an impression of the fibre remained on the metal.

With perfectly dry fibres, compression in a dry atmosphere at 100° C. produced effects similar to those obtained at lower temperatures. All the fibres experimented with were permanently deformed when compressed in contact with water at 100° C. The result obtained with wool is shown in fig. 5, A. The difference in luminosity, as seen in polarised light between crossed nicols, of the compressed and uncompressed portions, fig. 5, B, is mainly due to variations in thickness. Wool fibres treated in this manner do not return to their original shape when boiled in water while loose, because none of the internal stresses produced by the compression remain.

This was proved by subjecting a wool fibre to extension, until the interference colour shown in polarised light changed, and then boiling the fibre in water, when the colour returned to that shown before extension, and the fibre itself showed no tendency to return to its original length when placed loosely in boiling water.

Experiments made at different temperatures showed that no permanent deformation was produced by compressing wool fibres in contact with water below 80° C. for five minutes; longer times were not used.

Cotton fibres exhibit similar properties in boiling water, but the amount of permanent deformation is not so great as that produced on wool by similar treatment, and some of the internal stresses remain.

The results of the experiments already described show that in the dry state textile fibres exhibit a kind of plasticity, in which strains produced by externally applied stresses are accompanied by corresponding internal stresses; both strains and internal stresses disappearing when the fibres are placed in cold water. The effect of heat on dry fibres, up to the temperature 100° C., is not to alter the nature of this plasticity; it may, however, alter its magnitude, but this has not been investigated. Water at the ordinary temperature removes this plasticity, and causes the fibres to become elastic; they are deformed by stress but return to their original shape on removal of that stress, unless the elastic limit has been passed. The elastic limit appears to be higher for wool than for other fibres. At high temperatures water renders fibres truly plastic, externally applied stress produces deformation, but little or no internal stresses. Cotton retains some of the internal stresses, but wool appears not to do so.

The quantitative measurement of these properties presents difficulties, on account of the small dimensions of many of the fibres. The author hopes to be able to overcome these difficulties later.

The experiments already mentioned throw some light on the differences in the impression given to the sense of touch by fabrics composed of different fibres. In the act of feeling fabrics, the individual fibres are bent considerably, and it is in the resistance to bending, and the tendency to unbend when released, that the real difference lies.

It is extremely difficult to imitate the act of feeling fabrics with such small quantities as are required for microscopic examination, but an idea of the manner of bending of fibres was obtained by twisting them so as to form loops. An ordinary fibre of English wool bends like an indiarubber cord, forming wrinkles on the inside of the loop (fig. 6, A). Hollow fibres, which are by no means uncommon in Scotch wool, bend like an indiarubber tube, with flattening of the central canal at the bend.

As already mentioned, bent wool fibres return to their original shape in water, or more slowly in a moist atmosphere, when free to move. In practice, it is known that the impression given to the sense of touch by fabrics composed of wool is to a large extent dependent on the amount of moisture present in the fabrics. Thus the deductions which may be drawn from the experiments described are in accordance with practical facts.

Ordinary cotton fibres, on account of their hollow ribbon-like structure, bend at very sharp angles, see fig. 7, A. Fibres mercerised under tension, being more cylindrical, bend in a more circular curve, see fig. 7, B. Fibres mercerised while in a loose condition form wider loops than either of the other two. This is shown in fig. 7, C; a wider loop was formed in spite of the fact that more twists were present in the fibre. This is due partly to the increased diameter resulting from the transverse swelling, and partly to a difference in the colloidal state of the fibre substance produced by treatment. It is known that cotton fibres treated in this way feel more like wool than ordinary cotton fibres or those mercerised under tension.

The Cause of the Double Refraction of Textile Fibres.

The double refraction exhibited by cotton fibres has already been shown by the author* to be due to strains such as are produced on any elastic body by the application of stress. Such strains are permanent and are accompanied by internal stresses. The evidence brought forward in support of this view was the following:—

When cotton fibres are treated with an ammoniacal copper solution swelling takes place, and often barrel-shaped formations such as those shown in fig. 8, A, are produced. It is only in those portions which have not swelled or done so to a slight extent, as in the rings of the barrel-shaped formations, that double refraction persists, fig. 8, B.

A film prepared from a solution of cotton in ammoniacal copper solution shows double refraction only when subjected to stress, but retains this property when the stress is removed.

The direction of strain is parallel with the axis of the fibre. This was proved by turning the fibre about the plane of polarisation; it appeared darkest when parallel to or at right angles to the plane of polarisation and brightest when at 45° to that plane. The double refraction of the fibre is increased by stretching, hence the natural condition of cotton fibres corresponds to that produced by tension on an elastic body. The internal stresses are represented by a negative pressure acting along the axis, or a positive pressure acting in all other directions.

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* *Loc. cit.* (Refs. 3 and 4).

All the natural fibres examined appear to have internal stresses of the same kind as those present in cotton.

It is well known that many crystals exhibit double refraction, and many chemists attribute this to a particular type of molecular configuration or of crystalline structure. Since colloids such as indiarubber and cellulose exhibit double refraction only when subjected to stress, the effect of stress should be either to change the molecular configuration or impart some temporary crystalline structure to the colloid. It is difficult to see how the relatively small pressure required to impart double refraction to indiarubber could alter the configuration of its molecules, and there is no known method of proof applicable in this case.

In order to test whether stress imparts crystalline structure, X-ray photographs of pieces of stretched and unstretched indiarubber were taken by the Laue method, but no evidence of crystalline structure of any kind was obtained.

The most probable effect of stress on substances of colloidal nature is to alter the distances between the molecules or atoms composing those molecules, unequally in different directions.

Effect of Chemical Treatment on the Double Refraction of Fibres.

When cotton fibres are treated with concentrated solutions of sodium, potassium, or tetramethylammonium hydroxides,* they shrink in length and swell transversely, with almost complete removal of the central canal. Fibres treated in this way when turned about the plane of polarisation show almost equal illumination whatever their position with respect to that plane. From this observation, the author† concluded that the shrinkage in length was due to the balancing of the internal stresses.

Naegeli‡ observed that nitrated cotton containing less than 11·7 per cent. of nitrogen had positive double refraction, but that containing more than 12·5 per cent. of nitrogen showed negative double refraction. This latter corresponds to the condition produced on an elastic body by compression in the direction of the axis. The internal stresses would be represented by a positive pressure acting along the axis of the fibre. This is confirmed by the fact that stretching a highly nitrated cotton fibre reduces the negative double refraction, and eventually makes it positive.

Ordinary cotton fibres show numerous irregularities when examined in polarised light, which are not seen in ordinary light (fig. 9, A), and in transverse sections there is no evidence of a regular distribution of stresses (fig. 9, B). When treated with concentrated alkalies while under tension, the fibres show a somewhat regular distribution of the internal stresses, both longitudinally (fig. 10, A) and transversely (fig. 10, B).

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* Knecht and the Author, 'Journ. Soc. Dyers and Cols.,' vol. 28, p. 224, (9), (1912).

† *Loc. cit.* (Ref. 3).

‡ 'Ber. der Bayer. Akad.,' vol. 1, p. 307, (10), (1862).

Most of the comparatively thick fibres of English wool, when examined in polarised light, show different colours in various parts of the fibres. This is partly due to differences in thickness, as shown by the fact that portions change in colour when fibres are rotated on their axes, and partly to variations in the internal stresses.

A fibre of wool showing variations of the latter kind was held straight between two clamps and boiled for five minutes in water, when the variations disappeared, and the fibre showed even colouring. (Figs. 11, A and B, illustrate this experiment.)

The same fibre, after treatment, was stretched 25 per cent., when the colour changed except in that portion which before treatment differed from the rest of the fibre photographed. Further boiling in water while stretched again removed the inequalities in colour, fig. 11, D.

The results of this experiment point to inequalities in the physical state of the fibres in different portions.

The modifications in the condition of internal stress produced on wool fibres by boiling in water are similar to those produced on cotton fibres by treatment with concentrated solutions of alkalies. Cold water, although it removes internal stresses formed by the action of externally applied stress, has no effect on the naturally occurring internal stresses, which must therefore differ from the former kind.

The same difference has been observed with artificial fibres, and is undoubtedly due to the fact that the stresses present in the formed fibres are due to changes in volume, whereas externally applied stress produces only changes in shape.

The action of concentrated sulphuric acid on wool in modifying the internal stresses is illustrated by fig. 12. Sulphuric acid 1·80 sp. gr. caused swelling of the wool fibre (fig. 12, A and F), which was attacked first on the outside and gradually through to the inside. This is proved by the manner of removal of double refraction as shown by Photos A, C, D, and E. Treatment with cold water after 40 minutes in contact with the acid caused return of the double refraction and transverse shrinkage of the fibre (Photos G and H).

As would be expected from this experiment, the physical properties of the wool were changed considerably by the treatment. Such wool was found to be unshrinkable, and when stretched extended much further before breaking than ordinary wool. The maximum effect was given in the time taken to completely change the whole of the fibres.

The Probable Causes of the Internal Stresses Existing in Natural Fibres.

In order to ascertain in what manner internal stresses could arise in fibres, experiments were made with artificial fibres. A concentrated solution of gelatine was run through a fine capillary tube into alcohol, and the resulting threads rapidly dried in a current of air. On examination in polarised light these fibres showed double refraction similar to the natural fibres. This property is due to internal stresses arising from the drying of the jelly. Although shrinkage would occur in all directions, the stresses due to shrinkage lengthways would act on the whole cross-section of the fibre, whereas those due to shrinkage towards the diameter would be concentrated on it, consequently, the pressure acting transversely would be greater than that acting longitudinally.

Fibres prepared from gelatine in the above manner, when placed in water, swelled rapidly and the double refraction disappeared but no shrinkage lengthways took place; the swelling transversely, however, was greater than that longitudinally. Treatment of the gelatine fibres with formaldehyde vapour prevented the removal of double refraction by cold water.

Fibres were prepared by forcing viscous solutions of cellulose into a coagulating liquid; the resulting fibres, although wet, were doubly refracting. The internal stresses present in such fibres are formed during the forcing of the viscous solution through the fine capillary, and made permanent by solidification. The same cellulose solution, forced through the capillary into the air, swelled out as it left the capillary, presumably owing to the effect of the internal stresses. It is obvious that, the more viscous the material, the longer the time required for the balancing of internal stresses, and, with a very viscous material, even a slow process of coagulation would be quite sufficient to make the stresses permanent.

Artificial silk is made by forcing cellulose solutions into a coagulating liquid, the resulting fibres being eventually dried under slight tension. Such fibres show double refraction quite strongly, and, under the action of stress, heat, and moisture, behave in a similar manner to ordinary cotton fibres. It is thus possible to produce, artificially, fibres having internal stresses similar to those present in the natural fibres.

There are several possible causes for the internal stresses present in the natural fibres. If fibres are composed of spindle cells, which have themselves originated from spherical cells, the forces which produced the change are obviously those of extension, and in a viscous or plastic body would produce

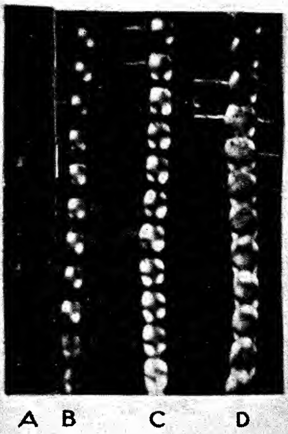


Fig. 1

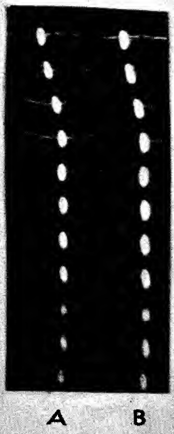


Fig. 2

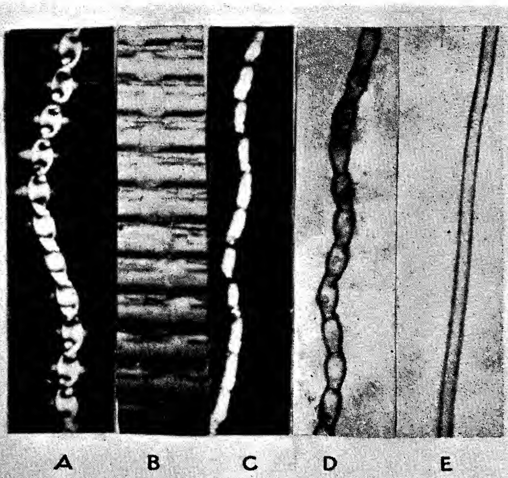


Fig. 3

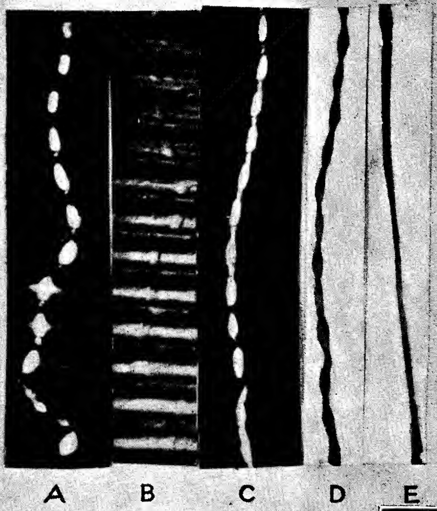


Fig. 4

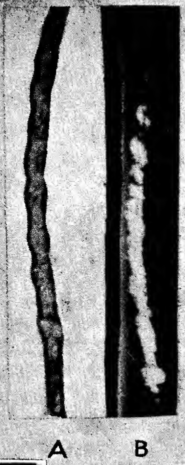


Fig. 5

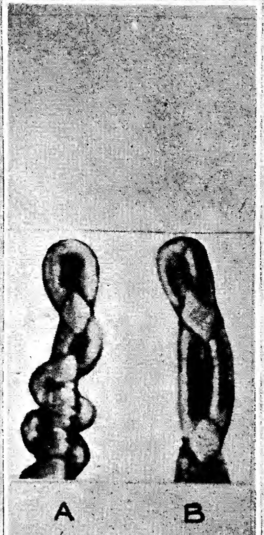


Fig. 6

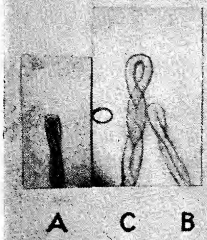


Fig. 7

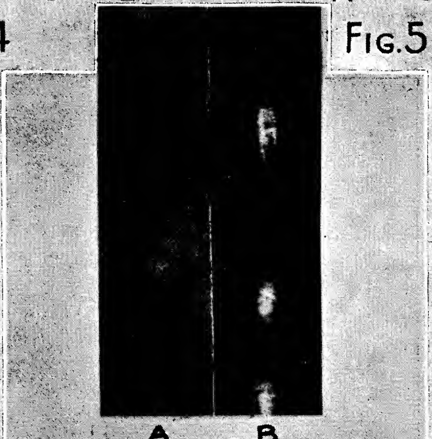


Fig. 8

Fig. 9

FIG 10

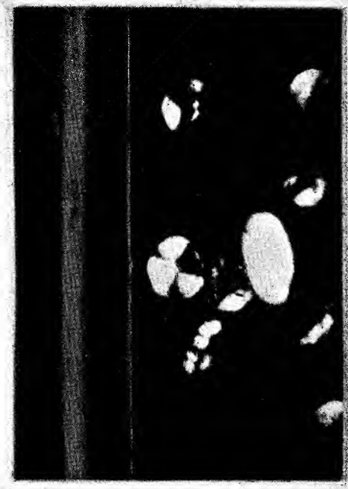


FIG 11

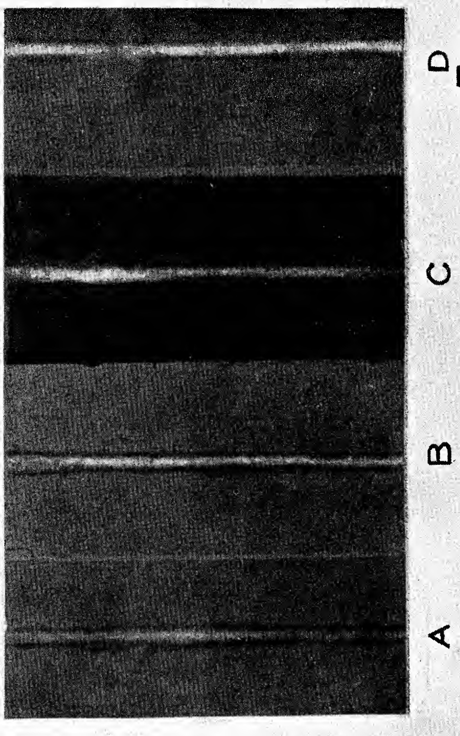
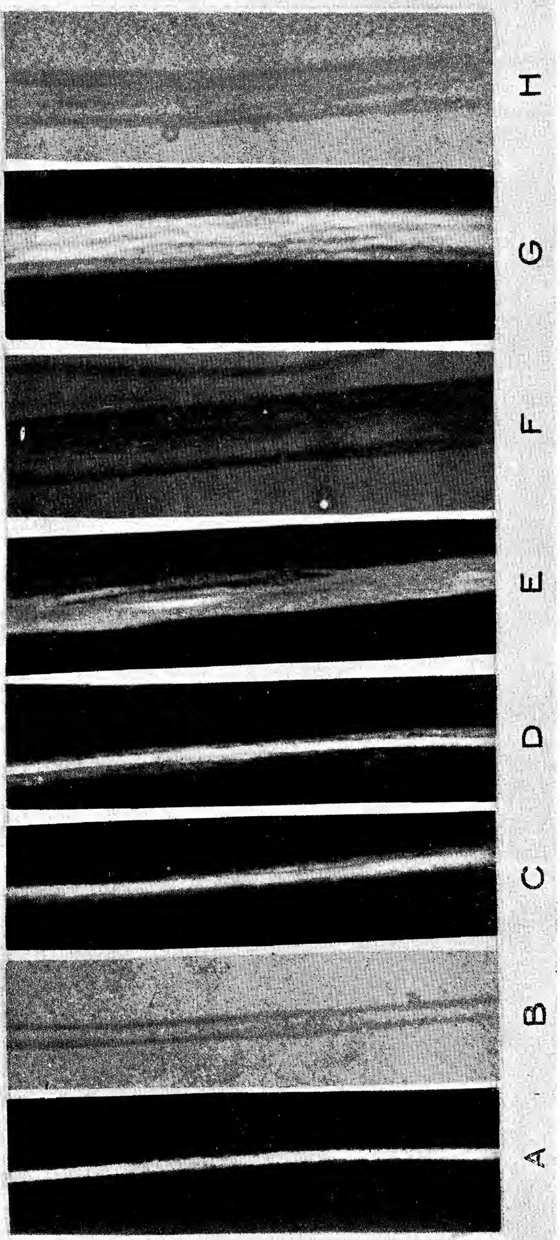


FIG 12



internal stresses similar to those in natural fibres; such stresses would be made permanent by the coagulation of the viscous material.

A phenomenon of this kind occurs when a drop of oleic acid is placed in a 10-per-cent. solution of ammonia, cylindrical formations arise which show double refraction. This is one of the well known cases of the so-called liquid crystals.

On the other hand, if fibres are formed by the forcing, probably by osmotic pressure, of a viscous or plastic material through a nozzle or pore in the skin of a seed or an animal, conditions will arise similar to those discussed with reference to cellulose solution.

It is likely that the air plays some part in the hardening of the materials of which the natural fibres are composed.

DESCRIPTION OF PLATES.

Plate 5.

Fig. 1.—A fibre of English wool as seen in polarised light between crossed nicols in various stages of compression on a grooved celluloid plate.

Fig. 2.—A cotton fibre in two stages of compression.

Fig. 3.—A, a wool fibre compressed on a grooved celluloid plate, polarised light; B, the impression produced on the celluloid, ordinary light; C, the wool fibre after removal of pressure, polarised light; D, the same seen in ordinary light; E, after immersion in cold water.

Fig. 4.—A similar set of experiments to the above, with a fibre of mercerised cotton.

Fig. 5.—A wool fibre compressed under boiling water on a grooved aluminium plate. A, ordinary light: B, polarised light.

Fig. 6.—Illustrating the bending of wool fibres. A, an ordinary fibre of English wool; B, a hollow fibre from Scotch wool.

Fig. 7.—Illustrating the bending of cotton fibres. A, a fibre of Egyptian cotton; B, mercerised under tension; C, mercerised without tension.

Fig. 8.—A fibre of Egyptian cotton swelled by treatment with a saturated solution of copper carbonate in ammonia of sp. gr., 0·880, showing barrel-shaped formations. A, ordinary light; B, polarised light, crossed nicols, showing internal stresses in narrow portions.

Fig. 9.—Fibres of ordinary Egyptian cotton as seen in polarised light between crossed nicols. A, whole fibre; B, transverse sections.

Plate 6.

Fig. 10.—Fibres of mercerised Egyptian cotton. A, whole fibre; B, transverse sections.

Fig. 11.—A fibre of English wool as seen in polarised light, crossed nicols. A, original fibre; B, after boiling in water five minutes; C, the same fibre stretched 25 per cent.; D, the stretched fibre boiled in water for five minutes.

Fig. 12.—Illustrating the action of sulphuric acid of sp. gr., 1·80 on a fibre of English wool. A, original fibre, polarised light; B, the same, ordinary light; C, the fibre after one minute treatment with the acid; D, after 5 minutes; E, after 30 minutes; C, D, and E in polarised light; F, after 35 minutes, seen in ordinary light; G, the same fibre treated with cold water after 40 minutes in contact with the acid, seen in polarised light; H, the same in ordinary light.

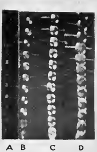


FIG. 1

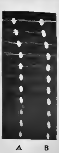


FIG. 2

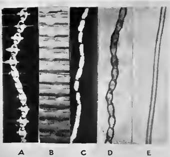


FIG. 3

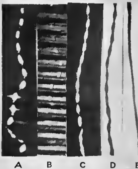


FIG. 4

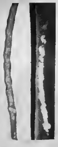


FIG. 5

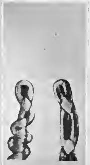


FIG. 6

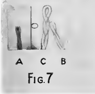


FIG. 7

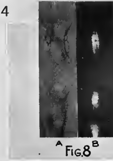


FIG. 8

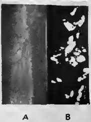


FIG. 9

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Fig. 6.—Illustrating the bending of wool fibres. A, an ordinary fibre of English wool; B, a hollow fibre from Scotch wool.

Fig. 7.—Illustrating the bending of cotton fibres. A, a fibre of Egyptian cotton; B, mercerised under tension; C, mercerised without tension.

Fig. 8.—A fibre of Egyptian cotton swelled by treatment with a saturated solution of copper carbonate in ammonia of sp. gr., 0·880, showing barrel-shaped formations. A, ordinary light; B, polarised light, crossed nicols, showing internal stresses in narrow portions.

Fig. 9.—Fibres of ordinary Egyptian cotton as seen in polarised light between crossed nicols. A, whole fibre; B, transverse sections.

FIG 11

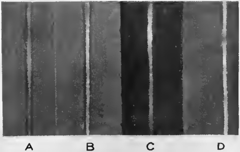

FIG 10

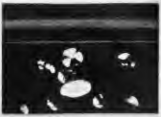

FIG 12

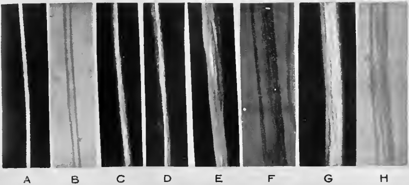

PLATE 6.

Fig. 10.—Fibres of mercerised Egyptian cotton. A, whole fibre; B, transverse sections.

Fig. 11.—A fibre of English wool as seen in polarised light, crossed nicols. A, original fibre; B, after boiling in water five minutes; C, the same fibre stretched 25 per cent.; D, the stretched fibre boiled in water for five minutes.

Fig. 12.—Illustrating the action of sulphuric acid of sp. gr., 1·80 on a fibre of English wool. A, original fibre, polarised light; B, the same, ordinary light; C, the fibre after one minute treatment with the acid; D, after 5 minutes; E, after 30 minutes; C, D, and E in polarised light; F, after 35 minutes, seen in ordinary light; G, the same fibre treated with cold water after 40 minutes in contact with the acid, seen in polarised light; H, the same in ordinary light.